END

FILMED

DTIC

||||| 1.0 ||||| |||28 |||2.5
||| 3.2
|||36
|||40 |||2.2
||||| 1.1 |||2.0
||||1.8
|||||1.25 ||||1.4 |||1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

DOT/FAA/PM-84/25
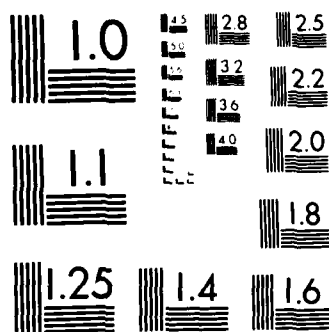
Program Engineering
and Maintenance Service
Washington, D.C. 20591

AD-A153 512

Evaluating Wind Flow Around Buildings on Heliport Placement

J.B. McKinley

Systems Control Technology, Inc.
2326 S. Congress Ave., Suite 2A
West Palm Beach, Florida 33406

October 1984

Final Report

This Document is available to the public
through the National Technical Information
Service, Springfield, Virginia 22161.

DTIC
ELECTE
MAY 9 1985

D

US Department of Transportation

Federal Aviation Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/PM-84/25	AD-A153512	

4. Title and Subtitle		5. Report Date
EVALUATING WIND FLOW AROUND BUILDINGS ON HELIPORT PLACEMENT		November 1984
		6. Performing Organization Code

7. Author's)	8. Performing Organization Report No.
J.B. McKinley	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Systems Control Technology, Inc. Champlain Technology Industries Division 2326 South Congress Avenue, Suite 2-A West Palm Beach, Florida 33406	
	11. Contract or Grant No.
	DTFA01-80-C-10080, Mod.31
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	13.
U.S. Department of Transportation Federal Aviation Administration Program Engineering & Maintenance Service Washington, D.C. 20591	Final Report Sept. 1983 through Aug. 1984
	14. Sponsoring Agency Code
	APM-720

15. Supplementary Notes

16. Abstract

This report presents a heliport wind assessment methodology for evaluating and potentially minimizing the influences of building-induced wind on heliport operations.

Descriptions and illustrations of wind flow patterns and characteristics for both isolated and multiple building configurations are provided to assist heliport planners, operators, and helicopter pilots in understanding the problems associated with building-induced winds. Based on geometric flow patterns, general guidelines for ground level and rooftop heliport placement are provided.

Additional guidelines for determining the area of wind influence about isolated and multiple building configurations are detailed. Rules for calculating the distance from the sides of buildings for heliport siting is provided, as well as, rules for calculating the area of influence from any wind direction. Lastly, rules are defined for calculating the area of influence of buildings with respect to the prevailing climatic wind conditions.

Recommendations are delineated for further data gathering and evaluation to validate and enhance the heliport wind assessment methodology.

17. Key Words	18. Distribution Statement
Heliport Helicopters Wind Flow Turbulence Downstream Wakes	This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	42	

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

iii

LIST OF TABLES

1.0   EXECUTIVE SUMMARY

This document is the product of a Heliport Wind Effects Workshop and
an in-depth literature review. The workshop held on 8 December 1983,
functioned as a round-table discussion to present necessary information
sources, technology requirements, and proposed wind assessment
approaches. The workshop participants included prominent wind
engineering researchers, a helicopter aerodynamicist, a helicopter pilot,
and an FAA representative. The key participants are listed in Table 1.1.

The overall study was conducted through a literature survey of
historical data analysis to support the results of the wind workshop, and
guide in the development of a wind assessment methodology to determine
the severity of winds about a heliport or proposed site.

The results of the workshop having a direct bearing on the procedures
described in Section 3.0, are as follows:

- The inherent stability of helicopter operations
  in gust speeds well above the recommended
  operating manual limitations is well established
  by civil and military pilot experience.

- Helicopter operations are usually limited to
  reported conditions of lesser gust speeds (<20
  kts) for passenger comfort.

- Pilots become knowledgeable of what winds may be
  expected about a building or heliport facility
  through familiarity with varying wind conditions.

- Rooftop helipad approaches are performed at high
  speeds and steep descents. Normally they are
  more accessible because approaches can be made
  into the wind.

- Wind effect problems increase with steeper
  approaches depending on the direction of the
  shear (horizontal or vertical). Vertical shear
  is worse for shallower approach angles.

- Helicopters are operationally safer at higher
  approach speeds.

- IFR approaches may be more critical than VFR,
  since the pilot has no visual cues as to the
  wind conditions near the helipad. At the DH or
  MAP, the pilot would have limited lateral
  distance to respond to winds and transition to
  land.

Table 1.1 Heliport Wind Effects Workshop Participants

Individuals	Position	Accomplishments
Dr. Jack Cermak	Director of Research Wind Tunnel Laboratory Colorado State University	Wind Modeling of more than 300 Buildings Actual Heliport Wind Evaluation for a Building in Houston
Dr. Bernard Etkin	Professor of Engineering Institute for Aerospace Studies The University of Toronto	Building, Terrain, and Aircraft Wind Tunnel Modeling Consultant to Aircraft Industry Heliport Wind Evaluation for Rockefeller Building
Dr. Walter Frost	Director, Atmospheric Science Division The University of Tennessee Space Institute	Boundary Layer and Aircraft Wind Tunnel Modeling, and Field Measurements Validation Evaluation of Wind Effect on Helicopter Operations
Mr. Ray Prouty	Chief, Stability and Control Hughes Helicopters	Helicopter Aerodynamicist Honorary Fellow of American Helicopter Society Lecturer and Published Author 35 Years Rotor & Wing Experience
Dr. Dave Surry	Associate Research Director Boundary Layer Wind Tunnel Laboratory The University of Western Ontario	Building and Terrain Wind Tunnel Modeling Including Several Heliports Actual Heliport Wind Evaluations for Rockefeller Univ. Bldg.
Mr. Matt Zuccaro	President Eastern Region Helicopter Council, Inc.	Experienced Helicopter Pilot Operating in New York Metropolitian Heliport Environment
Mr. Hisao Tomita	FAA, APM-720	Advisor to VFR/IFR Heliport Design Guide Development

- Wind measurement instrumentation located 20 to 30 feet above the pad would be sufficient provided it could be transmitted to the pilot in IMC.

- Most published wind characteristic data presents only horizontal component data since it is more commonly measured. This is because horizontal hot-wire probes are normally chosen in wind tunnel testing; and turbulence measured from vertical hot-wire probes are difficult to interpret.

- In most cases an IFR heliport could be said to have no significant wind problems due to the fact that the required airspace will be obstruction free. The exception is if the heliport is on a rooftop.

- Typical building configurations can produce vastly different wind (gusting) conditions.

- Pictorial representation of wind flow may be more helpful to the pilot or planner than statistical data and wind energy parameters.

- Wind flow over and around buildings is governed by two parameters: building height and width. In developing a wind evaluation methodology, keep typical building considerations to a minimum.

- Advanced rotorcraft need not be considered as they tend to have disk loadings in excess of 10 lb/ft², and are therefore less susceptible to gusts.

- Further simulation modeling and wind tunnel testing is necessary to relate the helicopter's performance to the levels of wind experienced about a building, in order to develop assessment guidelines.

- If available, full scale helicopter data should be collected and correlated with full scale and model scale wind data.

- Wind assessment analysis should be used as a "design tool" and not a "regulatory tool".

1.1 DEFINING THE PROBLEM

There are different opinions on whether wind is actually a problem for helicopter operations near heliports. The first point usually made is that modern helicopters can and often do operate in adverse wind and gusting conditions beyond their recommended design operating limits. This is particularly true for EMS helicopters and U.S. Coast Guard operations. Therefore it is often argued that helicopters can operate in adverse wind and gusting conditions without incident. Incidently, wind was not considered a probable cause of fixed-wing aircraft accidents until cockpit data recorders were installed in aircraft. Consequently, as data recorders were analysed, wind was found to be an attributable factor to many accidents. Vertical and horizontal wind shear could have been a factor in more accidents than was previously believed. For the same reason it is also possible that wind may be a causal factor for more helicopter accidents and incidents than is presently believed.

It is an inherent property of helicopters that they are less sensitive to gusts than are fixed-wing aircraft. This results from the "powered lift" aerodynamic characteristic of the helicopter in which lift, especially in low-speed flight, is not dependent on the relative wind that is altered by gusts.

Another opinion states that, based on the 200,000 annual operations in the New York City area without any incidents attributable to wind, wind is not a factor in accidents. However, it is also known that some operators will not fly into the New York City area when gusts speeds are from 35 to 40 knots. Although not all operators have the same operating practices, this example does show that there is a sensitivity to wind and a knowledge of the potential for adverse conditions caused by wind. It should also be stated that these operating practices are more often based on passenger comfort than on concerns for safety.

Pilots also become accustomed to the winds about a heliport into which they frequently operate, and therefore do not consider known, anticipated winds as a problem.

Wind conditions could change, however, with the construction of a nearby building, or become a more important factor during IFR operations at the heliport. For the case of IFR operations, it should be understood that the airspace associated with IFR will have to be obstruction free. The volume of this airspace is much larger than that needed for VFR operations. Therefore, high winds will more often be a primary problem associated with IMC conditions and building influence as a secondary factor. Nevertheless, visual cues during IMC operations are not always available, so even normal windy conditions could prove to have a worsening effect on pilot performance.

In summary, proficient and professional helicopter pilots do agree and have demonstrated that helicopter operations can be performed

successfully to center city heliports as in the New York City area even
during very windy and gusting conditions. It has always been the pilots'
discretion whether or not to make approaches to heliports based on the
pilots' knowledge of anticipated winds. These heliports have been in
place for many years and have accommodated many helicopter operations.
In the background of the FAA's National Prototype Heliport development,
and the advent of many more center city, public use heliports, it would
be desirable to have a method to determine whether a heliport placed at a
certain location may experience advantageous or adverse winds. In a
center city environment, winds about a heliport could be significantly
influenced by neighboring buildings that are already established.
Heliport sites are more often selected based on a demonstrated need for
helicopter operations at a specific location. However, in planning for a
specific site, if winds are determined to be potentially adverse during
high demand periods, then another nearby site may be selected that can
also meet the demand but with less severe winds to make helicopter
operations more favorable. For these reasons, methods and guidelines for
evaluating the potential wind effects around buildings and heliport
facilities may prove useful in site selection and providing for more
favorable helicopter operations.

1.2 EVALUATING POTENTIAL WIND EFFECTS

The wind characteristic data presently available does not provide
sufficient information to allow development of an accurate heliport wind
assessment tool. Further wind tunnel testing is necessary to provide
data on more typical building shapes and sizes. In addition, data need
to be gathered at other heights along the building rather than the
surface only. Furthermore, the level of building-induced winds needs to
be related to the operating performance (or pilot preferred) limitations
of the helicopter. This is best provided through simulation of
helicopter response qualities in gusts and downstream wakes.

As a step in this direction, Section 2.0 provides pictorial
illustrations of wind flow characteristics about both single and multiple
building configurations. The intent is to familiarize helicopter pilots
and heliport operators or planners with typical flow patterns that may
affect a heliport.

To assess winds at heliports, Section 3.0 describes a proposed
methodology for determining the area of wind influence at a heliport site
or facility, relative to the helicopters operating there. This
discussion points out the type of wind tunnel or helicopter data
necessary for each procedure outlined. Finally, an example is presented
to clarify the use of the methodology.

2.0   WIND PATTERNS AROUND BUILDINGS

This section presents a description of wind flow patterns and characteristics for both isolated and multiple building configurations. The intent is to provide the reader unfamiliar with boundary layer wind effects, with a general understanding of air flows about buildings that may be applied to heliport siting and evaluation. The figures presented in this section originate from References 1 and 2.

As air flows over a surface, the velocity of the closest layer of air decreases towards zero, due to the frictional drag of the surface. Conversely, the velocity increases with increasing distance from the fixed surface until, at some distance from the surface, there is no perceivable reduction of air velocity. The layer of air near the fixed surface is known as the boundary layer. Its thickness may vary from a few millimeters for the smooth surface of small bodies to about 1600 feet in the atmospheric flow over built-up areas of the earth's surface.[1] It is well documented by wind tunnel and analytical evaluation, that the nature of the earth's surface wind motion (the earth's boundary layer) is affected by changes of terrain features. Terrain features such as, open country, sea coasts, high altitude inland country, rural neighborhoods, and built up metropolitan areas, produce different flow acceleration, separation and turbulent effects. Air flow over an obstruction is largely governed by the viscosity of the air, which in turn influences the sliding or shearing of adjacent layers. Viscosity also hinders the sudden changes of flow direction. For low air speeds and small obstructions, the shearing forces will tend to produce smooth and streamlined air flows. At higher air speeds over larger obstructions, inertia of the air flow will predominate over the shearing forces and tend to become turbulent flow.

As an introduction to wind flow around actual buildings, Figures 2.1 and 2.2 illustrate wind flow separation for both a curved surface obstruction and sharp edged obstruction, respectively. As shown in Figure 2.1 the flow over a curved surface is most pronounced. Because the obstruction is curved, separation can occur at different positions, and is strongly influenced by the degree of turbulence in the flow. For flow over a sharp edged object, as shown in Figure 2.2, separation is largely produced by the edge itself, producing a less smooth and streamlined air flow. Most buildings, particularly those found in cities, can be classified as sharp edged. However, the flow about a building becomes more unpredictable and complicated to determine when it is in close proximity to other buildings of various sizes and shapes. It then becomes evident that individual building shapes are not as important as the configuration of buildings of various sizes and shapes. This report will attempt to present such configurations of buildings with anticipated wind flow. Before this is done, it may be helpful to understand the effects of wind flow about isolated buildings of various shapes and sizes.

ROOFTOP HELIPORT PLACEMENT

1. Turbulent wake interaction with helicopter operations can be substantially reduced on rooftop heliports by having the helipad elevated into the streamline wind flow above the turbulence region. (See discussion on Figure 2.9 and 2.10). If the climate exhibits persistent predominant winds from one direction throughout the year, placement of an elevated helipad on the leeward edge will be preferred. If the prominent wind direction changes substantiatly at different times of the year, elevated helipad placement in the center of the building is preferred. The distance the helipad could be elevated to pentrate the turbulent flow layer is estimated to be 0.5 times the building's height for buildings under 100 feet tall. For buildings 100 feet and taller, a maximum of 50 feet elevation appears to be sufficient for most conditions. A penthouse style structure on which the helipad would rest would be quite adequate. (This elevation rule is derived from guidelines in Reference 16 and further developed from data in References 7 and 13).

2. Preferably, the helipad should be elevated such that there is a clear space of at least six feet in height between the pad and the supporting roof. This will prevent additional turbulent flow from being generated, and allow more streamline flow over the pad.

Least preferred heliport placement locations are described in the following guidelines.

3. Rooftop locations on a shorter building predominantly leeward of a taller building will be subjected to considerable turbulence. This effect is illustrated in Figure 2.8, with the winds from the opposite direction, however.

4. Heliport placement on lower levels of multi-level roofs will experience turbulent flow in the immediate vicinity of the heliport, as shown in Figures 2.9, 2.10 and 2.13.

GROUND LEVEL HELIPORT PLACEMENT

1. The preferred placement location would be the predominant windward side (front) of the building, presuming no other building(s) substantially blocks the wind flow.

2. If the windward side of the building is not available, equally preferred locations would be along the buildings sides that are essentially parallel to the predominant wind flow. This is presuming that no other buildings are adjacent to the sides.

3. If the sides of the building described in 1 and 2 above are not available, then the location on the leeward side of the building would be preferred. Placement at this location has the disadvantage of having areas of undesirable turbulent flow over the helipad through which the helicopter may have to traverse.

Heliport placement areas least preferred are summarized in the remaining guidelines.

4. Locations between adjacent buildings, both facing the wind, as shown in Figure 2.7, will exhibit stronger wind flows than the free-stream wind through which the helicopter will have to traverse.

5. The location between two building, as shown in Figure 2.8, when the predominant wind attacks either building's face will be conducive to considerable turbulence.

6. Locations within and downstream of the narrow passage formed by two separate sections of buildings, as in the venturi effect (Figure 2.11), will experience much higher velocity winds than the free-stream wind. Locations downstream will also be subjected to considerable turbulence and wakes. This condition exists if the predominant wind direction is essentially parallel to the axis and attacks the wide end of the venturi formation.

7. Heliport locations sheltered by other buildings, as illustrated in Figure 2.14, may experience considerable turbulence during transition to and from the heliport, depending on the approach and departure paths and the presence of other building groups.

19

The characteristic wind patterns for the previously described
building configurations do not attempt to explain the more complicated
and unpredictable vertical and reverse flows or turbulence intensity.
However from these simplified geometric flow descriptions, general
guidelines for heliport placement in the vicinity of buildings is
possible. This is because the more pronounced wind flows about a
building appear to repeat expected geometric patterns. These patterns
will vary in a more unpredictable manner depending on the amount of
turbulence in the flow.

The purpose for providing general guidelines for heliport placement
is to assist heliport planners and developers in determining the area
of least and most turbulent wind interaction with helicopter operations.

Observing the figures in Sections 2.1 and 2.2 yields two important
characteristics about wind flow around a building or buildings: (1)
velocity streamline flow, and (2) downstream turbulence and wakes.
review of the wind interaction illustrated by Figure 2.3, an area
turbulent flow and eddies develops in an area windward of the building
the wind strikes the face. Along the leading corners of the building
around which the wind is escaping, high velocity streamline flow
generated. As this streamline flow continues along the building
it separates and forms eddie currents. As these flow patterns enter
the open area behind the building and mix with wind flow falling
top of the building, intense turbulent flow is generated. This flow
will persist in the form of wakes a considerable distance downstream
before it diminishes. Similarly, flow over the roof will exhibit
velocity flow as it rises over the leading edge. This flow will be
more turbulent as it separates from the roof further downstream.

These two typical characteristics are further magnified by the
presence of other buildings or structures, as discussed in Section
Based on these characteristics and the geometric descriptions of wind
flow in the previous two sections, the following general guidelines for
heliport placement are presented for ground level and rooftop heliports.

It should not be interpreted from these guidelines that heliports
should never be placed in locations of downstream wakes, turbulence,
high velocity flow fields. Neither do these guidelines imply that
locations are hazardous to helicopter operations. The helicopter
aerodynamically has proven to be more forgiving to gusts than fixed
aircraft. However, to avoid frequent passenger discomfort, or the
possibility of averted operations due to large gust speeds, other
heliport placement locations may be preferred.

The actual determination of distances from buildings for preferred
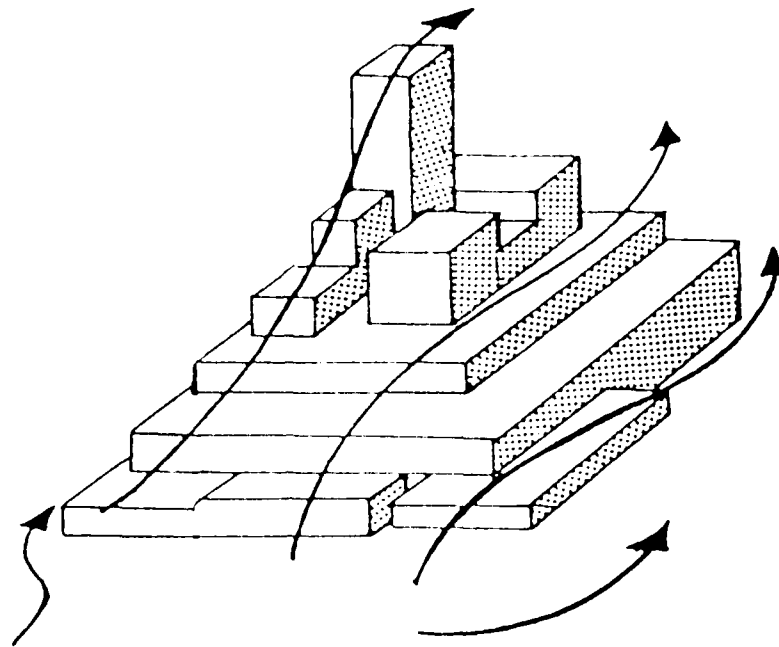heliport placement is illustrated in Section 3.0.
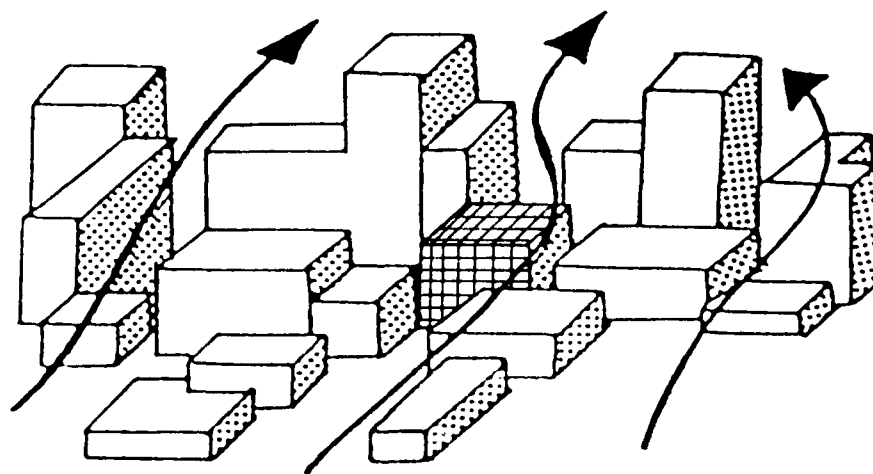
Figure 2.13 Pyramid Effect
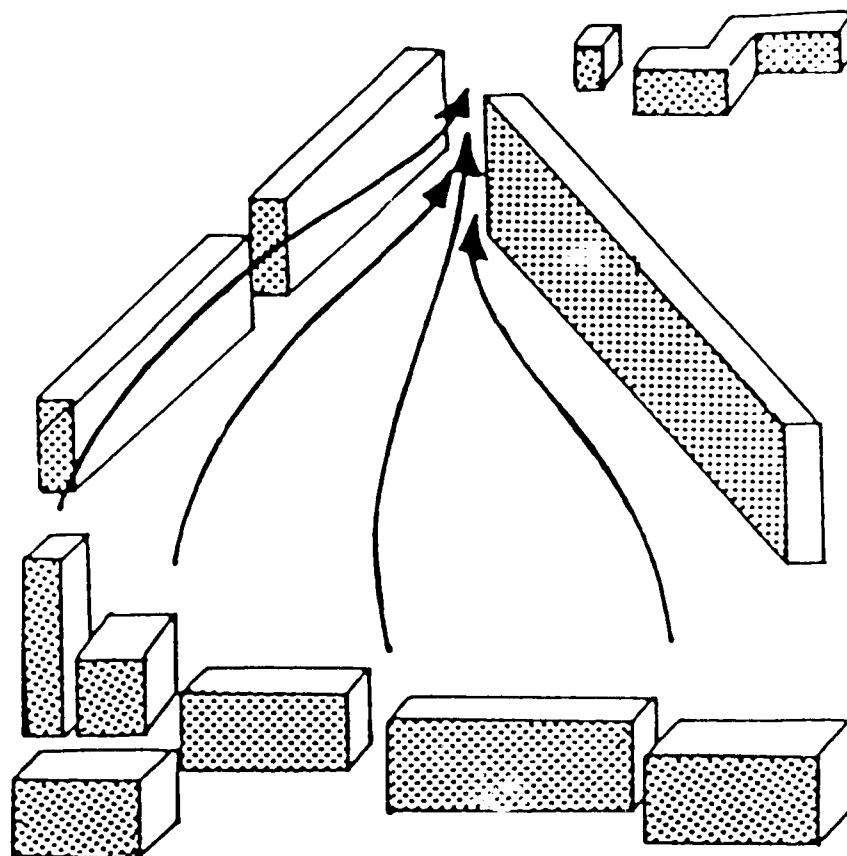

Figure 2.14 Shelter Effect
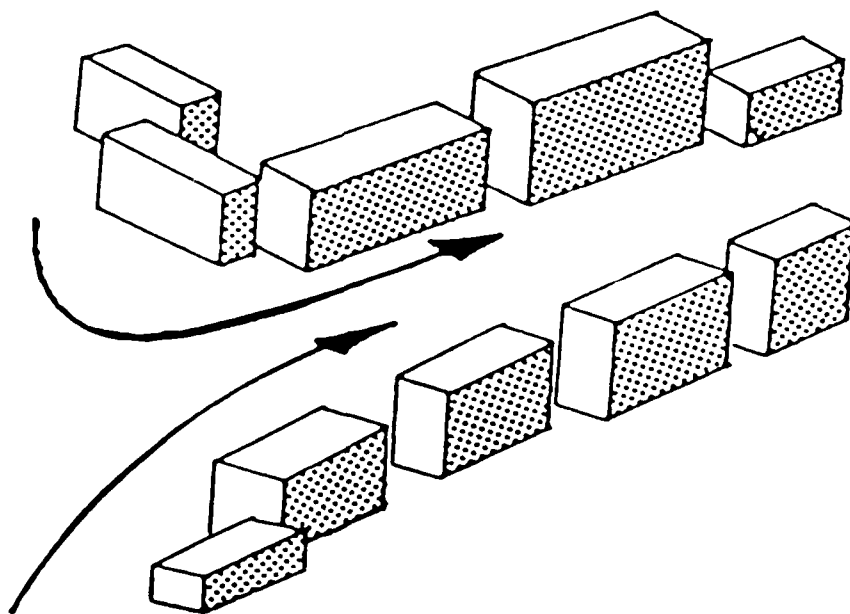
Figure 2.11 Venturi Effect

Figure 2.12 Channel Effect

16

There are a number of other complex building configurations that generate unique wind effects. The first of which is called the venturi effect, a funnel phenomenon produced by two separate sections of buildings whose axes make an acute or right angle, as illustrated in Figure 2.11. For the venturi to occur, the minimum height must be greater than 45 to 50 feet or about 5 stories, and the total length of the buildings should not be less than approximately 400 feet. The venturi effect is particularly evident when the environment upwind and downwind is free of other buildings for an area roughly equivalent to the venturi area. The most critical depth of the venturi opening will be two to three times the mean height of the building. Airspeed can be greatly increased in the venturi if the buildings roughly approximate curved surfaces. This is not a common architectural style.

The channeling of air flow discussed previously, can also be produced by a set of buildings forming a channel or an open gully. Normally this building configuration will not generate accelerated wind speeds unless the buildings themselves offer little resistance to velocity and have relatively small spacing between the buildings, on the order of less than three times the building height. The channel effect is shown in Figure 2.12.

Pyramidal configurations of buildings may produce an effect similar to that discussed previously for multiple roofs. Because this building configuration is made up of aerodynamic geometries composed of steps, balconies and other levels of roofs, this kind of structure does not offer a strong resistance to wind. As shown in Figure 2.13, the critical zones are at windward corners of the basic pyramidal structure, and on the windward multiple roofs of the structure.

The placement of buildings as in Figure 2.14, can present what is known as the shelter effect. With this arrangement, the windward buildings take the brunt of the wind flow and consequently shelter those low lying areas and buildings immediately behind them. One unique situation occurs in this building arrangement if there is an approximate 1500 square foot or larger open space into which the wind will fall, such as behind (leeward) the hatched building in Figure 2.14. The peripheral buildings' sides and recessed area will be exposed to turbulent air flow. The shelter effect may be restored, if the presence of buildings continue for approximately 700 feet further.

In summary, this section presents a number of unusual wind effects and anomalies produced by various building configurations. General guidelines to aid in a cursory evaluation of heliport placement are provided in Section 2.3, based on air flow characteristics revealed in Section 2.0. The next step will be to approximate the influence areas produced by winds over such configurations, in order that heliport planners and designers can effectively select the most usable site for a heliport. This information will also be useful in determining the effect of potential building construction in the near proximity of existing heliports. Guidelines for determining the wind's area of influence around buildings is discussed in Section 3.0.
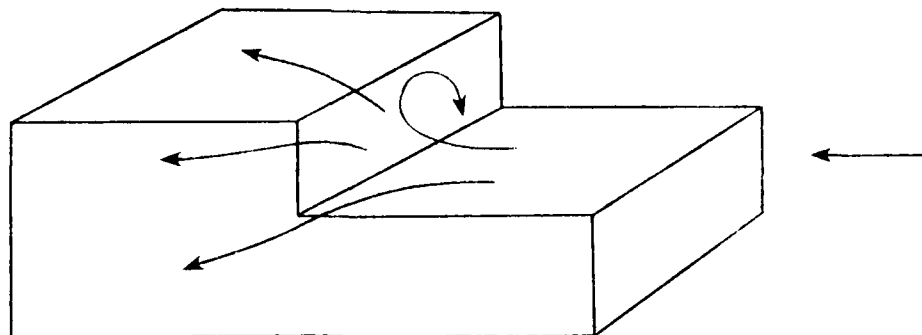
Figure 2.9 Step in Roof Level Contiguous to Outer Wall
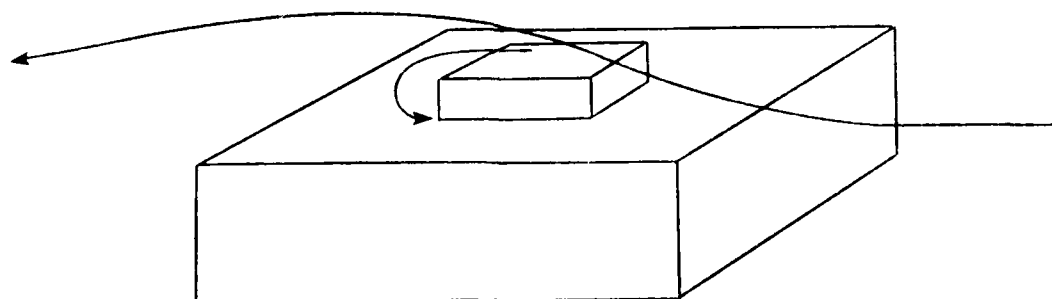

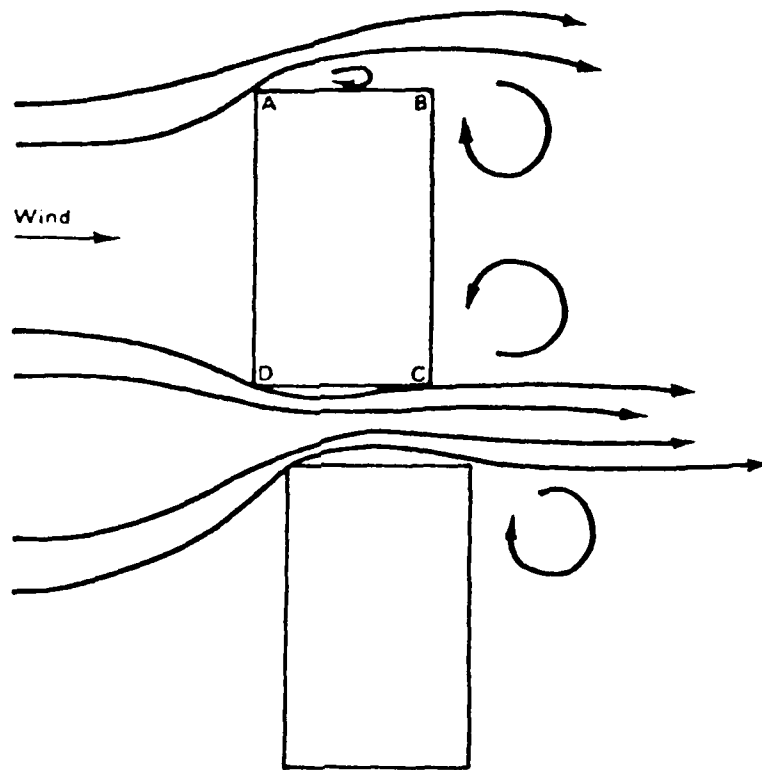Figure 2.10 Step in Roof Level Away from Outer Wall

14

Figure 2.7 Top View of Flow Between Adjacent Buildings

High speed
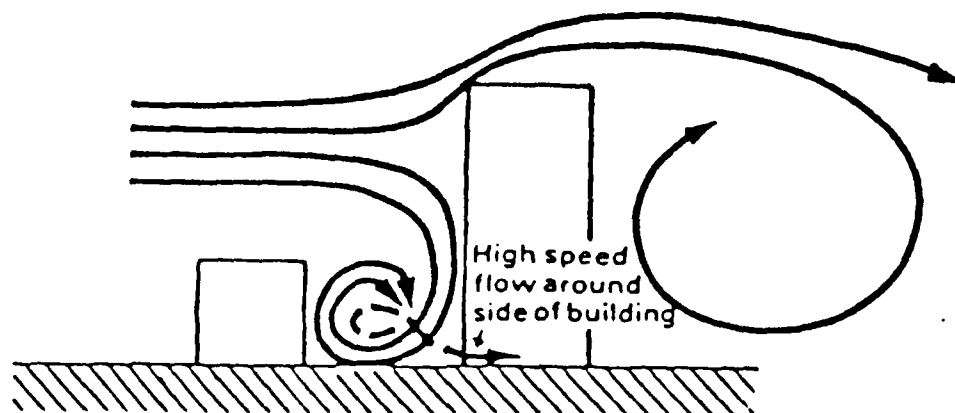flow around
side of building

Figure 2.8 Vortex Formation Between Buildings of Different Heights

13

2.2 MULTIPLE BUILDING CONFIGURATIONS

The presence of other buildings can also generate disturbing wind effects. In some cases, buildings may provide shelter, or they may channel the air flow in such a manner as to produce considerable high velocity winds and severe persistent turbulence that would ordinarily not occur for an isolated building. One configuration is when two buildings are adjacent to one another, as shown in Figure 2.7. The net result is wind being channeled and producing high wind speeds between the facing walls. The high wind speeds are greatest at the windward edges of the walls. Strong eddies and turbulence are generated on the leeward corners of facing walls. The flow pattern along the other walls is typical of that of an isolated rectangular building.

Another important building configuration to consider is that of a smaller building in front (windward) of a larger building. As illustrated in Figure 2.8, the smaller building generates a wake in the recessed area between the two buildings. This region will be an area of considerable turbulence, even though the mean speed of the air flow may be reasonably low. The turbulence is principally produced by the winds striking the large frontal area of the building and being diverted downward to lower levels. This effect produces large rolling vortices in the space between the buildings which escape along the lower sides of the taller building with increased velocities. In general, the most severe conditions occur when the tall building is leeward of the lower one, and is at least three times as high, and the gap between them is 0.4 to 1.2 times the height of the taller building.

Roofs at more than one level on a building can also produce some interesting wind effects. With a roof such as illustrated in Figure 2.9, the greatest amount of accelerated flow will be realized when the wind is attacking the higher roof leeward of the first roof. Local areas of turbulence will be generated as the wind strikes the leeward roof at the lower corners (x and y) and rolls both downward and off the sides. Winds from the opposite direction will produce similar incidents, although, with slower air flow speeds as the wind passes around the leeward corners of the upper roof and rolls up over the edge of the lower roof. Strong turbulence will be produced as the wind flows over the upper roof and falls onto the sheltered lower roof.

The building configuration in Figure 2.10, will have similar wind flow characteristics as those of Figure 2.9, for similar building dimensions. The relative height of the upper roofs in Figures 2.9 and 2.10, plays an important role in the type of air flow attacking the roofs. If the roof heights are small, they would be immersed in a turbulence region created by the lower buildings. If the roof heights are quite high, wind flow over and around the upper roof would be like any other building in an accelerated wind.
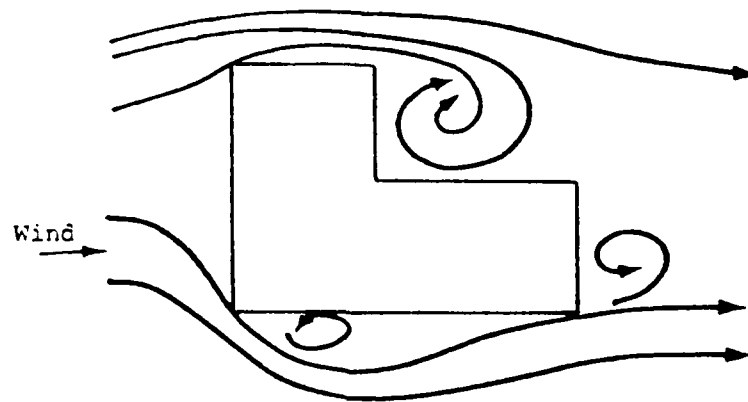
Top View of Flow

Figure 2.6 Flow Past L-Shaped Building with Wind Blowing Against Major
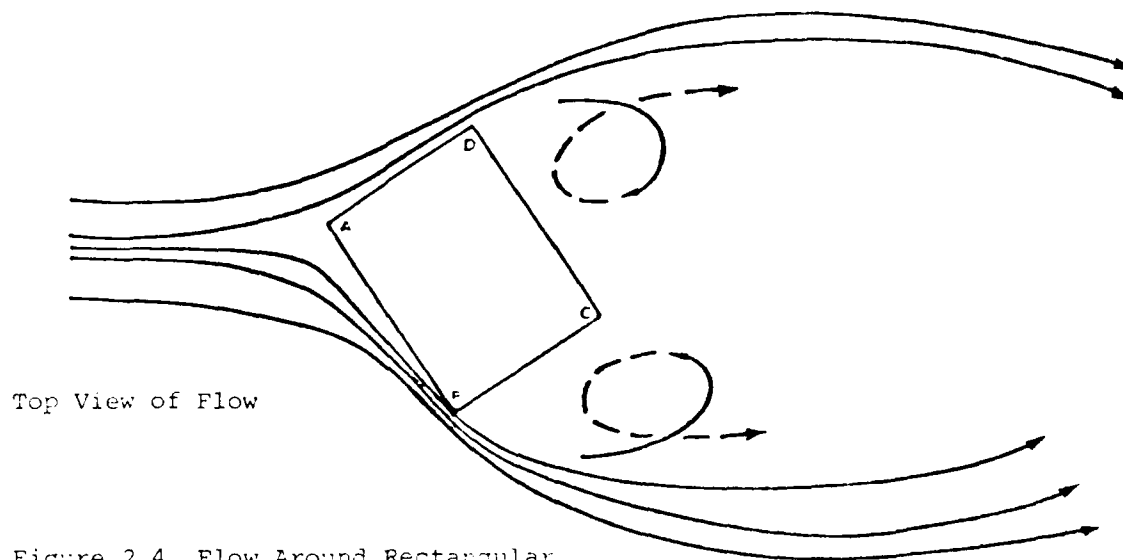Face

Top View of Flow

Figure 2.4   Flow Around Rectangular
             Building with Oblique
             Wind Incidence
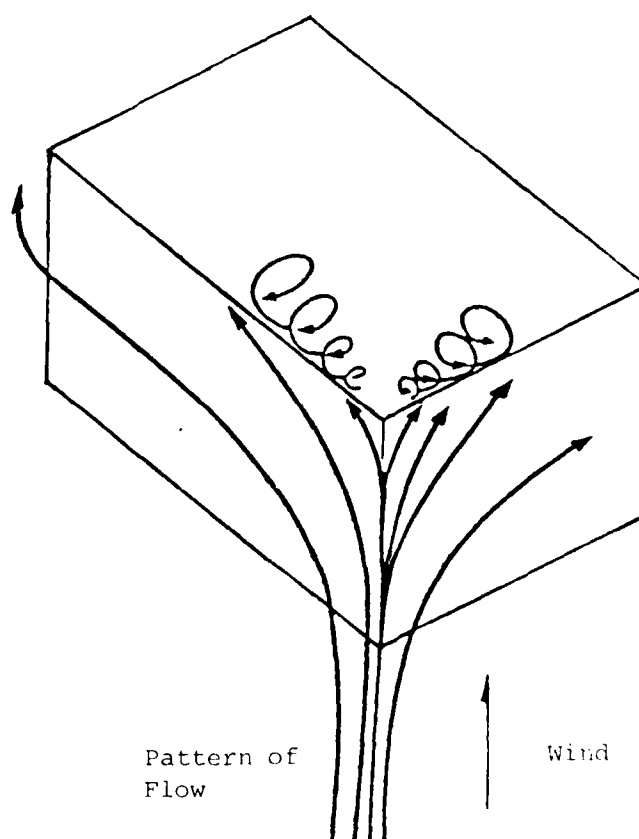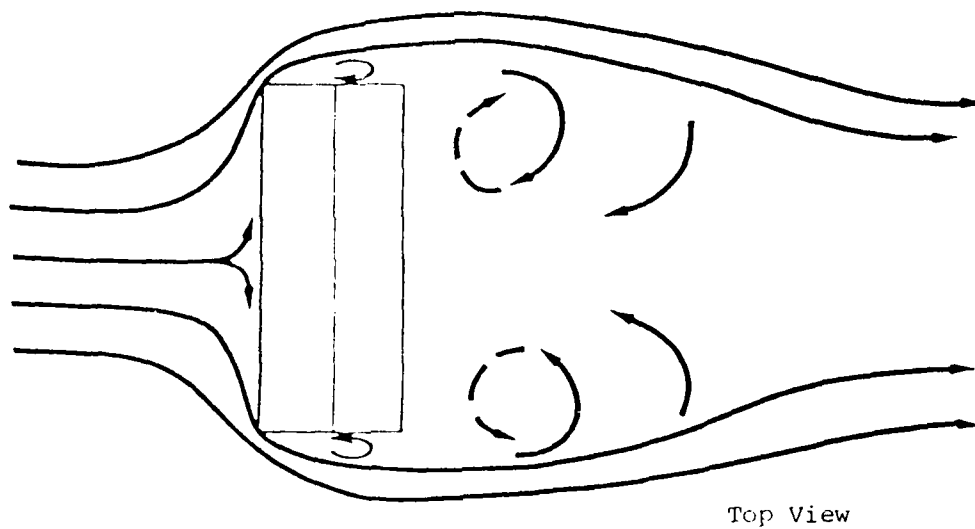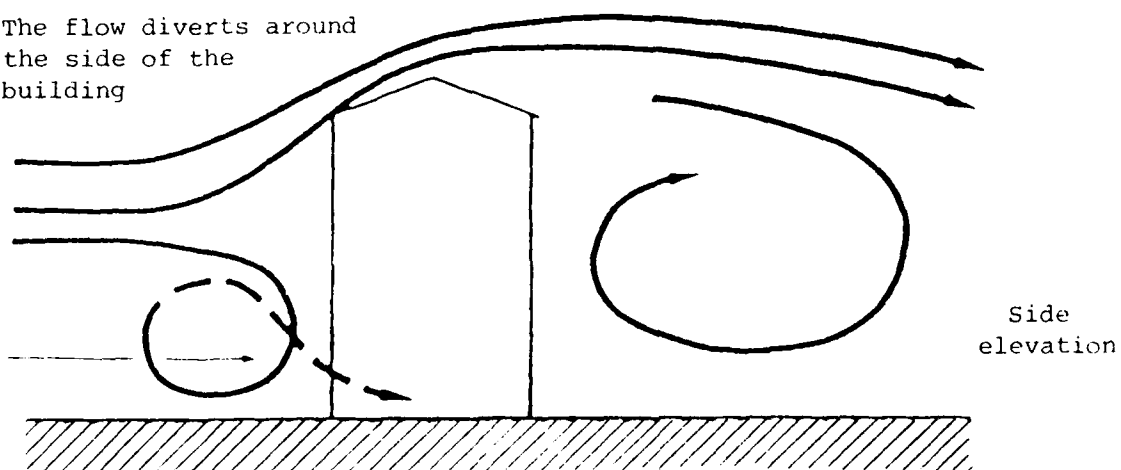
Pattern of
Flow

Wind

Figure 2.5 Flow Over Roof with Oblique Wind Incidence

Top View

The flow diverts around
the side of the
building

Side
elevation

Figure 2.3   Flow Past A Rectangular Building

9

2.1 ISOLATED BUILDING SHAPES

The remainder of this section will describe and illustrate wind about isolated buildings from various angles and for various shapes in order to describe the general characteristics of turbulent and streamline flow.

The first characterization, Figure 2.3, describes a rectangular building where the wind is approaching the building on its broadside. A portion of the wind falls downward against the face on the building and generates an area of low mean velocity turbulence on that face. The wind also diverts both over the roof and around the corners of the building. It can also be noticed in the side view of the building, that eddies form on the lower front face due to a downward flow of the wind. These eddies will continue to spiral along the lower front face and escape around the sides of the building and increase in speed. This escaping wind flow passes over the front or windward slope of the roof until the air flow separates from the surface. This separation depends on the pitch of the roof. The escaping wind flow tends to separate more easily from the low pitch roof than a steep one because of the inertia of the wind. Air flow separation also occurs more readily for tall buildings where the angle of elevation of the flow is greater. This description is also illustrated in Figure 2.3. From these figures it can be seen that the maximum streamline air flow speed occurs at the side and roof edges of the building.

Wind flow does not always strike a building normal to its face, but may strike it obliquely at a leading corner which divides the winds, as illustrated in Figure 2.4. As the wind moves along side A-B away from the initial impact, it begins to accelerate until it becomes near the leeward edge. As the air flow moves around the edge of the building along side B-C, eddies begin to form. The angle at which the wind strikes side A-D serves to increase the velocity of the air flow. The leeward side, D-C, will exhibit eddies and turbulent flow. Air flow striking a building obliquely presents a unique situation in that the air flow over the roof consequently will decrease, as shown in Figure 2.5.

The principal features of air flow about an L-shaped building are slightly more complicated, as shown in Figure 2.6. With the wind blowing in a direction normal to the face of the building it will be diverted around the building as with a rectangular shaped building, but it will be drawn into a large eddy in the recessed corner, from which the wind will partly escape downwind and partly spiral upward and join the flow over the roof. The flow distribution pattern will be similar to that for a rectangular building; however, there will be a reversed flow produced in the recessed area against the sheltered wall. Wind blowing from the opposite direction will produce flow patterns similar to those of rectangular buildings previously shown in Figures 2.2 and 2.3.

8
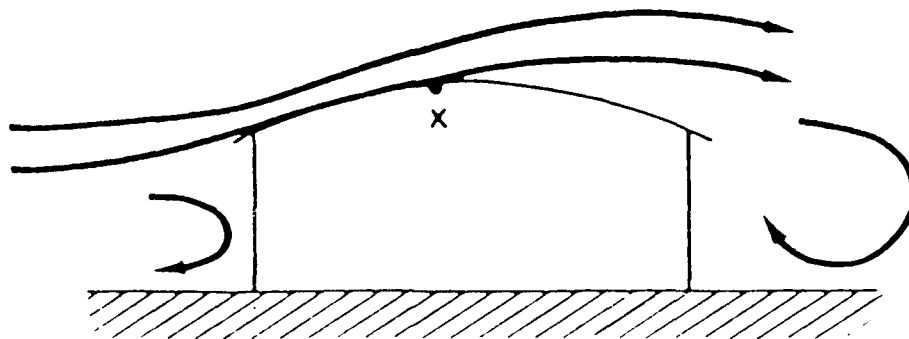
NOTE: Position of x determined by different flow
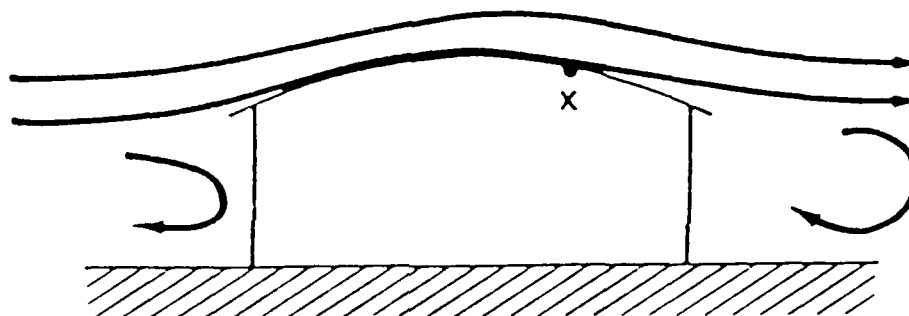speeds or upstream conditions.
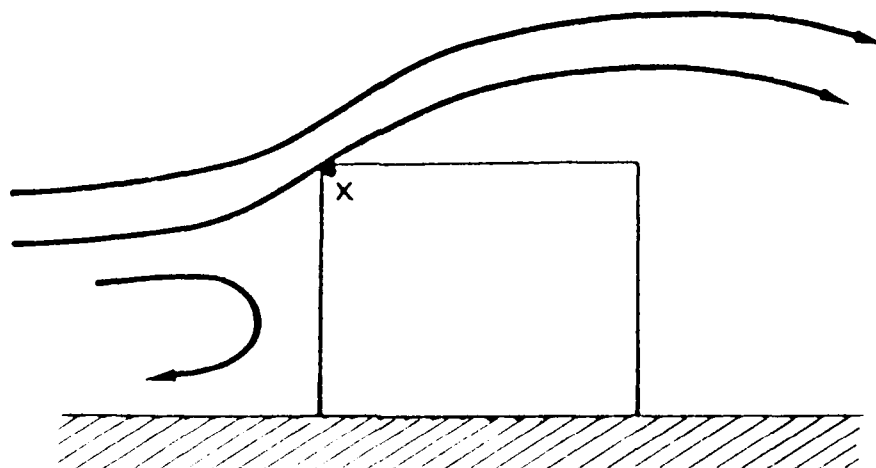

Figure 2.1 Flow Over a Curved Roof

Figure 2.2 Flow over a Sharp-Edged Obstruction

3.0   QUANTIFYING WIND FLOW AROUND BUILDINGS

There is a large compendium of literature documenting wind tunnel testing and simulation measurements of boundary layer winds around buildings. One major thrust of this literature is aimed at quantifying wind speeds on the surface in the near proximity to buildings to approximate pedestrian activity threshold or discomfort levels[2,3,4,5,6,15]. Another major thrust is the determination of wind loading pressures in determining compliance to building codes and regulations[1]. A third thrust is documentation on wake characteristics for various building shapes. Such fluid dynamic research has been performed for only specific building configurations[7-14]. Even less research has been performed for buildings regarding helicopter operations[7,8,12,16]. Data available from this research can not be extrapolated to buildings in other configurations without significant simulation efforts.

To develop these data necessitates simulation of helicopter handling qualities, and possibly wind tunnel testing of particular building shapes, multiple building configurations, and at various heights above the ground. It seems reasonable to be able to develop a methodology, based on data collected, to calculate the area of anticipated wind influence of particular interest in helicopter operations. The approach selected and subsequently discussed is founded on a methodology developed by Beranek[3] to determine the area and degree of wind influence on pedestrians at the ground surface near buildings.

Data lacking in the proposed methodology are the relative sensitivity of helicopter operations to the estimated winds about the buildings. Similar to the approach Beranek[4] and Gandemer[5,6] took in presenting discomfort parameters γ for various pedestrian levels of activity, helicopter performance parameters of γ could be postulated as a function of gust speeds. Several threshold values of γ could represent particular sets of helicopters based on sensitivity to gust speeds. Wind tunnel testing of various building configurations and combinations would then have two objectives:

1) Determine the area of wind influence at the surface and various heights about the building during conditions over which gust speeds for γ are exceeded.

2) Develop a set of parametric curves that would show the change in the area of wind influence for a constant γ as the building's height and base changes. These curves would be used to determine a particular building's area of influence relative to the types of helicopters anticipated to operate in its vicinity.

Based on these data, general rules could be developed similar to those of Beranek[3], for various heights about the building, in addition to

the ground surface. From this effort it may be discovered that the size of the area affecting helicopter operations is a greater influence than the maximum magnitude of γ itself. Depending on the height of the building, the area in which the maximum value of γ is exceeded may not encroach on the heliport's location. For example, a VFR heliport with a width of 50 feet and a transitional surface of a 2:1 slope, a building taller than 112.5 feet can be no closer than 225 feet from the helipad's edge. If γ is quite large, but exists over a smaller area than encompasses the example heliport, the magnitude of γ is unimportant. Therefore, the area for which a reasonable helicopter performance limitation parameter γ is exceeded will have a greater importance in determining heliport placement than how large γ becomes. This may also lead to the conclusion that the area of wind for a specific γ, at the ground near the building is greater than the area of wind at other heights about the building, which may therefore be neglected for most cases.

The general rules would be used to define the area of wind influence for certain levels of γ for a set of generalized building shapes and configurations.

The wind tunnel testing would further evaluate the effect of larger and smaller building shapes on the area of wind influence and change in γ as the height and base changes. Developing parametric curves of these data will provide a means for deciding whether a particular building may present difficulties to helicopter operations when gust speeds exceed γ.

General rules for determining the wind climate around the building would be the next logical step in quantifying the problem. This process could also assist in ascertaining heliport placement near the side of a building such that the wind influence would be minimized. The process would require plotting contours of hourly wind velocity represented by the percent of time wind is measured in sectors of 22.5°. Ratioing each to the percent of time that the wind is blowing in the prevailing direction and multiplying by the area of wind influence in that sector connects the properties of the building with the properties of the wind. These data when plotted will clearly describe the more important wind directions in relation to the building.

3.1 DETERMINATION OF THE WIND ENVIRONMENT AROUND ISOLATED BUILDINGS

The general rules and procedures described in this section are patterned after those of Beranek[3] but with particular emphasis on helicopter operations and helipad siting on and near buildings. It should be pointed out that these rules apply to buildings of a maximum height as tested by Beranek in the Netherlands, of 328 feet or 100 meters. Since many buildings in the U.S. are much taller, the wind tunnel analysis will be needed to validate these rules for heights above 328 feet.

These rules do not take into account one other important aspect that may influence helicopter operations; i.e., the downstream wake effect. This effect is known to persist a considerable distance downstream. The extent to which the area of the wake exceeds γ, requires further analytical evaluation. For the present analysis, a helicopter operating limitation parameter of γ = 1.6 is used. This parameter is largely a magnification factor of turbulence intensity. Validation of this parameter value is contingent upon further simulation of helicopter handling qualities and possibly, actual data collection.

3.1.1 Rules for Determining the Area of Wind Influence

The surface area influenced by the building can be determined by drawing a circle which defines the front and rear stagnation points. The radius R is calculated by equation (1) for a circle whose center is positioned a distance of e (equation 2) behind the windward face of the building. These rules are valid for 1.25 > h/a > 0.33, where h is the building height and a is the front width.

$$R = 1.6 \, (ah)^{\frac{1}{2}} \qquad\qquad (1)$$

$$e = 0.9 \, (ah)^{\frac{1}{2}} \qquad\qquad (2)$$

For tall buildings where h > 1.25a then a substitute height h' = 1.25a replaces h in equations (1) and (2). At times the value of e may be too large to realistically represent measure data. If so, another measured coefficient of 0.45 may be used in place of 0.9 in equation (2)[3].

For elongated bar shaped buildings, the radius R is principally dependent on the height of the building. Increases in widths where a > 3h may be neglected in the middle portion of the building, and the influence area sketched as for two separate buildings, yet joined in the middle, each with a width a' = 3h. These three types of building shapes are depicted in Figure 3.1.

Ascertaining the area of wind influence may be useful to heliport placement planning, particularly if helicopter operations at a helipad overlap with the area of influence from one or more buildings. Rules for calculating the distance from the front, sides, and rear of buildings to the edge of the influence area are provided in Figure 3.1.

To properly develop these rules and procedures for heliport application requires further wind tunnel investigation and analysis of existing data, to define typical building stagnation points relative to wind velocities and gust speeds at the preferred helicopter operating limits. Additional testing for buildings of heights greater than 328 feet should be considered to properly develop rules for areas of influence on rooftop or mid-level heliports.

3.1.2 Graphic Depiction of the Area of Influence

With the wind tunnel data derived as discussed in the previous paragraph to enhance the methodology, contour lines could be drawn for constant values of area A as a function of height versus width of the face of the building. The contour lines of area A would be used to determine the numerical value for the area of influence graphically expressed in Figure 3.1 and Section 3.1.1. Sensitivity analysis may show that several contour graphs are needed to represent significant differences in multiple building configurations, various heights along the building, and/or levels of γ for helicopter operating limitation groups. Such a graph[3] is illustrated in Figure 3.2. First note that this graph is accurate for a maximum building height of 328 feet (100 meters) and a width of 525 feet (160 meters). Also, the influence area A is relative to the ground surface near the building. As will be illustrated by an example in Section 3.2, the graph provides a convenient means on which to plot the height and width of the face of the building and subsequently read off the corresponding area A of wind influence.

There are three sections of the graph in Figure 3.2 that may be distinguished. The lightly shaded area beneath the lower contour would be used to indicate building sizes that do not introduce influence areas of a size significant to impact helicopter operations. The heavily shaded area in the upper portion of the graph would be used to represent building sizes that may exhibit a very large area of influence that can only be validated by wind tunnel testing. An alternative recommendation would be the selection of another site. The open area between the shaded areas would represent areas A that have been experimentally verified and may be interpolated from the graph for representative building heights and widths.

From the trend of the contours in Figure 3.2, two general conclusions may be drawn. One, for tall buildings, the area A is mostly dependent on the width a, and independent of increasing heights h. Two, for long buildings, area A is mostly dependent on height h, and independent of increasing width a. This relationship is expected to hold true for other contour lines derived for varying thresholds of γ and larger building dimensions.

3.1.3 Climatic Impact on Influence Area

Under certain conditions the determination of the wind influence area may not alone be sufficient to determine the favorability to helicopter operations. This is likely to be true for buildings having areas A that fall in the open or heavily shaded portions of the graphs, such as in Figure 3.2. The procedure presented in this section couples the wind properties of the building to the properties of the climatic winds. In this manner, two aspects become evident. First, the impact of local prominent winds may indicate favorable or worsening conditions at the

h >1.25a
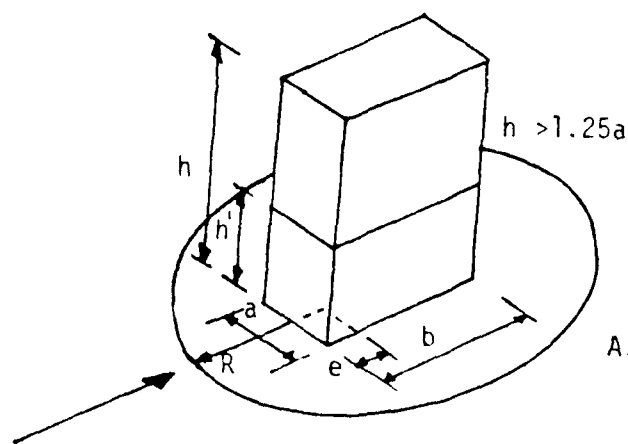
Distance to Edge of Influence Area from:
- Face = R-e
- Side = R-a/2
- Rear = R-(b-e)

A.

$R=1.6(ah')^{\frac{1}{2}} = 1.8a$

$e=0.45(ah')^{\frac{1}{2}} = 0.5a$

$(h' = 1.25)$

NOTE:

1) Arc defines area of wind influence.

2) The limits of the downstream wake may persist beyond the area of wind influence.

B.

$R=1.6(ah)^{\frac{1}{2}}$

$e=0.9(ah)^{\frac{1}{2}}$

h > 0.33a
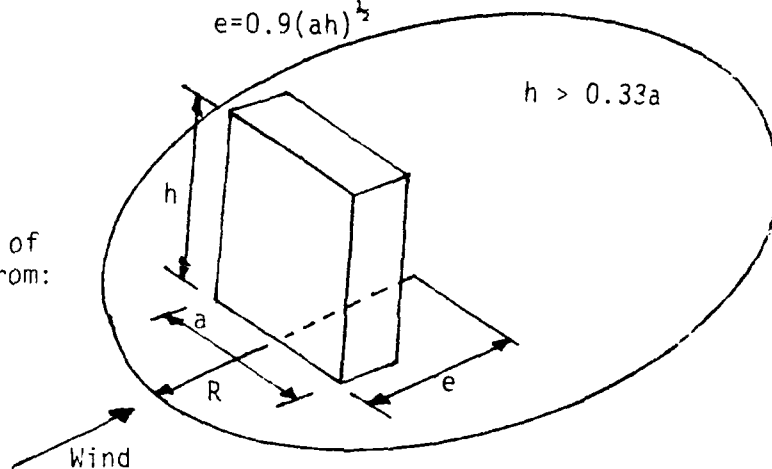
Distance to Edge of Influence Area From:
- Face = R-e
- Side = R-a/2
- Rear = R

Wind

C.

$R=1.6(a'h)^{\frac{1}{2}} = 2.8h$

$e=0.9(a'h)^{\frac{1}{2}} = 1.6h$

$(a' = 3h)$

Distance to Edge of Influence Area from:
- Face = R-e
- Side ≃ R-a'/2
- Rear = R

h < 0.33a

a'/2
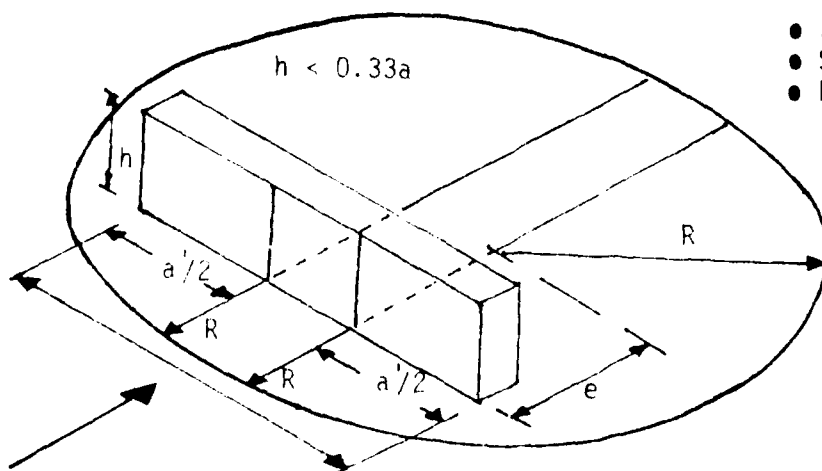
Figure 3.1   The Areas of Influence About Three Building Configurations
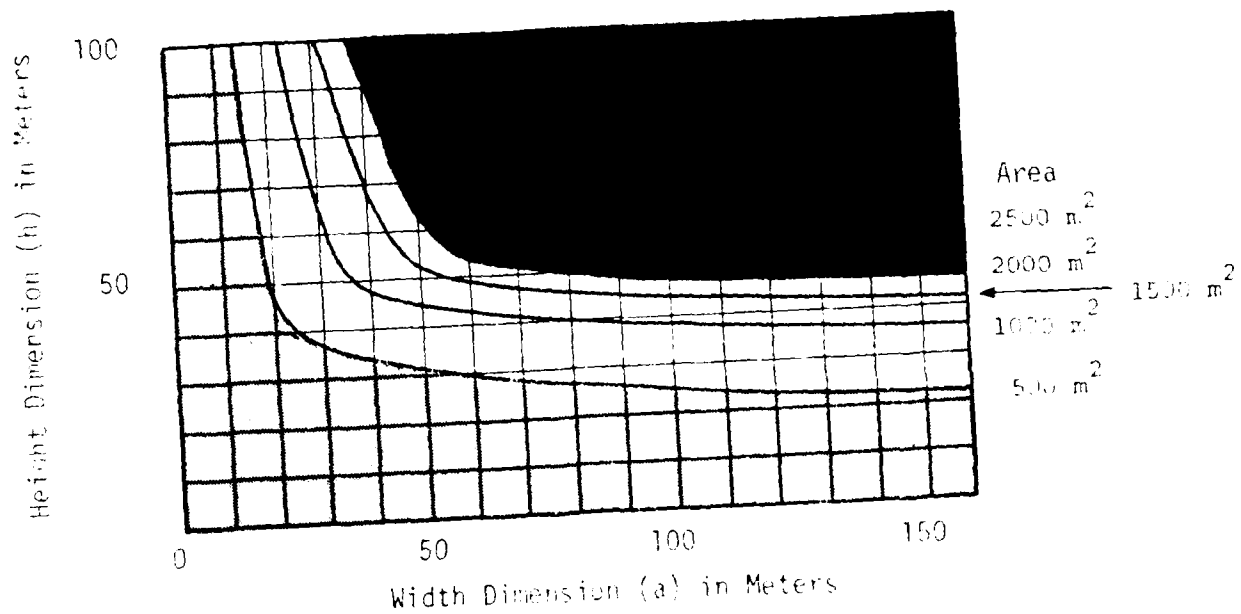
Area
2500 m²
2000 m² ← 1500 m²
1000 m²
500 m²

Height Dimension (h) in Meters

Width Dimension (a) in Meters

■ Windtunnel test recommended
□ Wind environment to be determined from the graph
□ Environment satisfactory

site. Second, changes in the building orientation upon wind influence can be observed. This would prove valuable in siting a heliport where a minimum of wind influence is demonstrated.

To perform this analysis requires the building or proposed building be oriented relative to North on a wind rose plot. The wind rose should be divided into equal sectors, such as 22.5°. Hourly wind velocity data would then be taken from a wind registration station in the vicinity, such as an airport or National Atmospheric and Oceanic Administration (NOAA) office. This set of data would then be plotted on the wind rose chart as a percentage of the time that wind is blowing in each 22.5° sector, t_ϕ. (See example analysis in Section 3.2).

The next major step is to calculate the building's area A_ϕ of influence in each of these sectors by equation (3). This equation roughly approximates the areas of influence for other wind directions.

$$A\phi \quad = \quad \frac{A_x + A_y}{2} \quad + \quad \frac{A_x - A_y}{2} (\cos 2\phi) \qquad (3)$$

where:
   A_x represents the influence area of the building by its front dimensions, and

   A_y represents the influence area of the building by its side dimensions

   ϕ represents the direction on the wind rose map from which the wind is blowing.

The values for A_x and A_y are determined by plotting the building's front and side dimensions on the graph in Figure 3.2 and reading off the area A. (See example in Section 3.2).

Following these calculations, the results of the first two steps would be combined in equation (4) to produce a measure of the climatic wind influence area W_ϕ, define as:

$$W_\phi = (t_\phi/t_o) A_\phi \qquad (4)$$

   where: t_o is the percentage of time that the wind is blowing in the prevailing direction.

When W_ϕ is plotted on the wind rose graph, the areas of least and most prominent building-imposed wind and climatic wind influence is clearly visible.

3.2 EXAMPLE OF WIND INFLUENCE AREA ANALYSIS

This section applies the previous discussion in Sections 3.1.1 through 3.1.3 to an example to illustrate the procedures of numerical evaluation of the wind environment. The numerical values used in this example originate from Reference 3.

The dimensions of the building in this example have a height h of 75 m (meters), a width a of 45 m, and a side or base b of 15 m. (Meters are used in this example for the convenience of not having to convert Figure 3.2, borrowed from Ref. 3, to English units). Determination of the influence area is accomplished with equations (1) and (2). The influence of the wind will need to be calculated for two directions, the face and side of the building. For wind on the face or x-direction, as shown in Figure 3.3, h/a = 45/75 = 0.6; that is, 1.25a)0.33a as in Figure 3.1b. Therefore, $R = 1.6 \ (ah)^{1/2} = 1.6 \ (75 \times 45)^{1/2} = 93$ m; and e = $0.9 \ (ah)^{1/2} = 52$ m.

For the wind influence at the ends of the building in the y-direction, as shown in Figure 3.3, h/a = h/b = 45/15 = 3.0; that is, h)1.25a, as in the building type in Figure 3.1a. Therefore, $R = 1.6 \ (ah')^{1/2} = 1.8a = 1.8 \times 15 = 27$m; and e = 0.5a = 7.5m.

For determination of the numerical values for influence areas for the x-component A_x and for the y-component A_y, the dimensions of the building are sketched on Figure 3.2, as shown in Figure 3.4. The values of $A_x \simeq 1300$ m² and $A_y \simeq 300$ m² are read from the graph as illustrated.

Since the determination of A_x lies in the region near the heavily shaded area of Figure 3.4, the impact of the building situation and/or helipad placement in relation to prevailing climatic conditions would provide additional useful insight. To do so, the first step would involve collecting hourly wind velocity data and plotting it as a percentage of total time t_ϕ the wind is blowing in a given 22.5° sector. This set of data may be plotted on a wind rose graph or by simply drawing a circle and dividing it into 16 sectors, as shown in Figure 3.5.

The next step is to calculate the wind influence area A_ϕ for each of the 22.5° sectors using equation (3). Since the building is oriented 10°E of North, 10° should be added to ϕ in the expression cos 2ϕ. This exercise determines the wind environment relative to the building for all sides.

To correlate the building's wind environment with the prevailing climatic conditions, equation (4) is used. In this example $t_o = 11.6$, the percent of time that wind is blowing in the prevailing direction. The resultant of equation (4) is the wind environment area W_ϕ for each 22.5° sector. The terms of equation (4) are tabulated in Table 3.1, and the results for W_ϕ plotted in Figure 3.6.

1.

$R = 1.6\sqrt{ah}$

$e = 0.9\sqrt{ah}$

2.

$R = 1.8a$

$e = 0.5a$

Figure 3.3   Example Building Situation and Influence Areas

Figure shows a graph with:
- Y-axis: Height Dimension (b) in Meters, with values 50 and 100
- X-axis: Width Dimension (a) in Meters, with values 0, 50, 100, 150
- Curve labels on right: 2500 m², 2000 m², 1500 m², 1000 m², 500 m²
- Points labeled A_y and A_x

■ Windtunnel test recommended

☐ Wind environment to be determined from the graph

☐ Environment satisfactory

$$A_x = 1300 \text{ m}^2$$
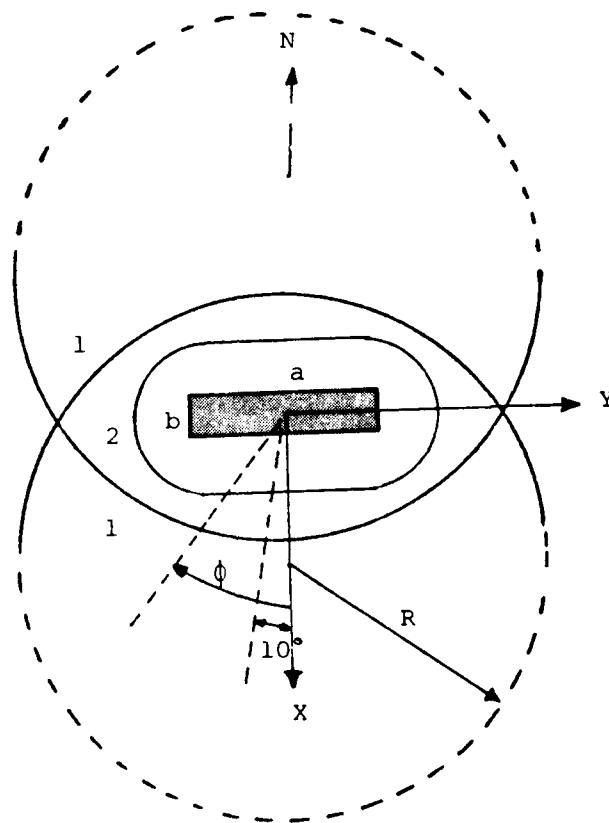$$A_y = 300 \text{ m}^2$$

Figure 3.4 Determination on A_x and A_y Influence Areas

From the contour plot in Figure 3.6, it is visible that the winds from the south are the most important for this particular building orientation. If the building is not already in place, determining the minimum wind influence for other building orientations is possible through iteration on equation (4). It is also clear from Figure 3.4, that the east or west locations would provide a more suitable heliport site, where the areas of wind influence are minimal. These locations would also be expected to have a more favorable effect on the final and initial phases of helicopter approaches and departures.

3.3 DETERMINATION OF THE WIND ENVIRONMENT AROUND MULTIPLE AND COMPLEX BUILDING CONFIGURATIONS

The general rules illustrated in the previous section for isolated buildings may be applied to more complex building configurations, given the following general guidelines. These guidelines are specifically for ground level heliport placement, since the rooftop heliport placement guidelines detailed in Section 2.3, would not be altered.

3.3.1 Determining the Area of Influence

Basically, building configurations can be categorized into complex isolated buildings and a collection of multiple buildings. To determine the area of wind influence for complex isolated buildings, such as the L-shaped building in Figure 2.6, the building should be separated into basic rectangular shapes. In this manner, the ground surface area influenced by the building can be evaluated by equations (1) and (2), and the rules defined in Section 3.1.1. The area of influence should be calculated and drawn for wind attacking the building from four quadrants, as in Figure 3.3. With a knowledge of the predominant winds, areas of minimum and maximum influence may assist in determining preferred heliport placement locations.

Collections of multiple buildings should also be separated into basic rectangular forms to simplify evaluation. Once the areas of influence for all buildings are drawn to scale, regions indicating overlap during times of predominant winds would be least preferred for heliport placement.

3.3.2 Determining Climatic Impact on Influence Area

The determination of the wind influence area may not alone be sufficient to evaluate the favorability to helicopter operations. The rules described in Section 3.1.3, which couple the wind properties of the building to the properties of the climatic winds, are slightly modified to accommodate complex isolated and collections of multiple buildings.

Again the buildings must be considered in basic rectangular forms. For complex isolated buildings, equation (5) is expanded from equation (3) to include any number of connected rectangular shapes.
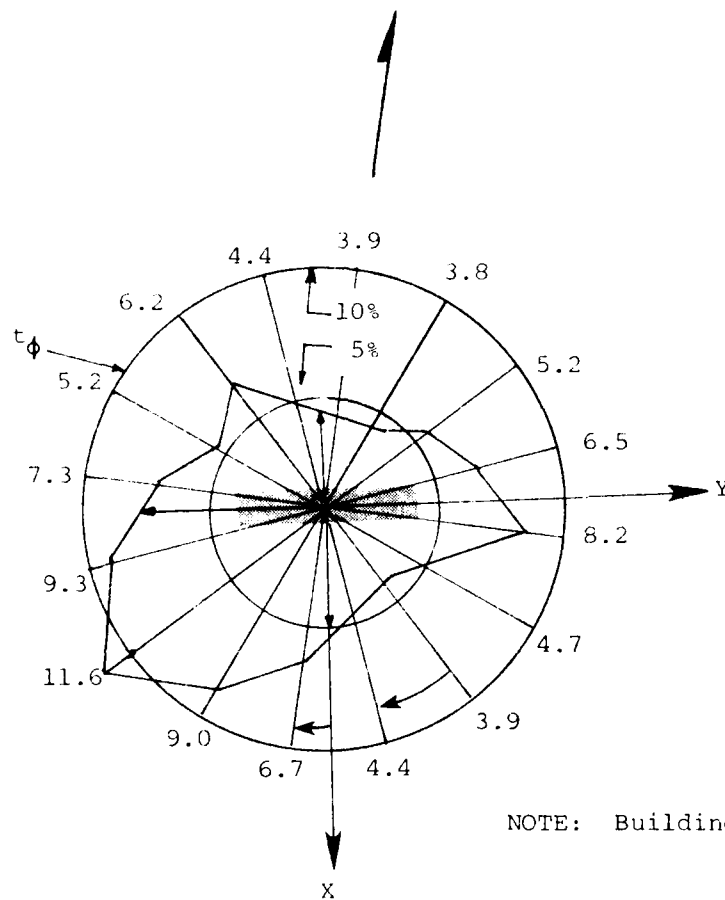
Figure 3.5 Contours of Hourly Wind Velocity as a Percent of Time
in Each Sector

Table 3.1 Numerical Expressions of Wind Environment

Sector	ϕ^*	ι_ϕ	t_o	A_ϕ	W_ϕ
1	10.0	6.7	11.6	1270	734
2	32.5	9.0		1011	784
3	55.0	11.6		629	629
4	77.5	9.3		347	278
5	100.0	7.3		330	208
6	122.5	5.2		589	264
7	145.0	6.2		971	519
8	167.5	4.4		1253	475
9	190.0	3.9		1270	427
10	212.5	3.8		1011	331
11	235.0	5.2		629	282
12	257.5	6.5		347	194
13	280.0	8.2		330	233
14	302.5	4.7		589	239
15	325.0	3.9		971	326
16	347.5	4.4	↓	1253	475

$^*\phi$ in 22.5° increments plus 10° building orientation from North.
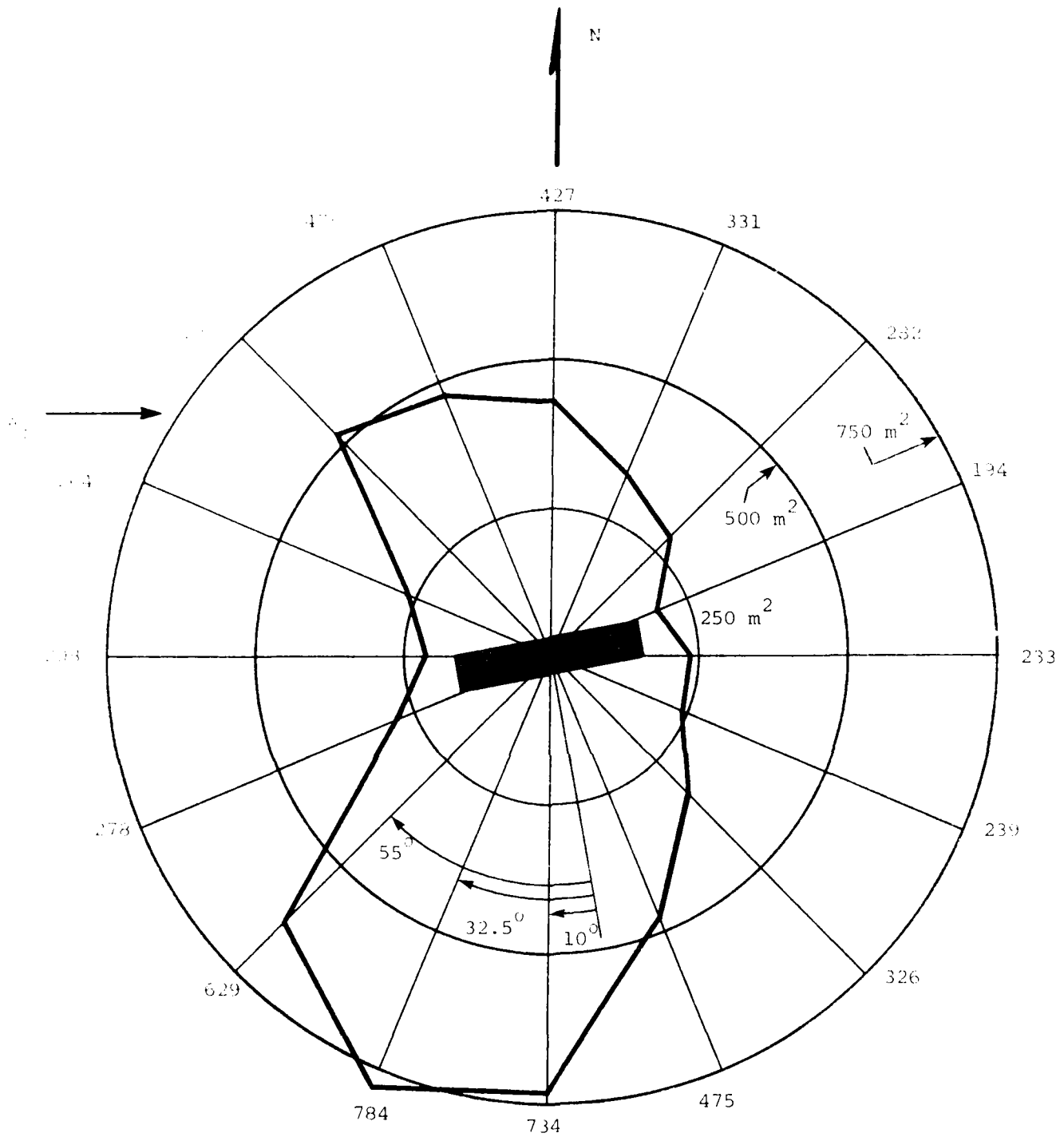
NOTE: Building not to scale.

Figure 3.6   Contours of Wind Environment Area W₅ Around a Building

34

$$A_\phi = \left[\frac{A_{x1} + A_{y1}}{2} + \frac{A_{x1} - A_{y1}}{2} (\cos 2\phi) \right] +$$

$$\left[\frac{A_{x2} + A_{y2}}{2} + \frac{A_{x2} - A_{y2}}{2} (\cos 2\phi) \right] +$$

$$\left[\frac{A_{xn} + A_{yn}}{2} + \frac{A_{xn} - A_{yn}}{2} (\cos 2\phi) \right] \qquad (5)$$

A_ϕ of equation (5) would produce a numerical value for the sum of the areas of influence of each basic rectangular shape, as the wind passes from any direction.

Similarly, equation (5) would be used for multiple building configurations; however, only for the buildings that exhibited influence area overlap, as determined by the guidelines in Section 3.3.1.

The remaining rules in Section 3.1.3 do not require modification to clearly identify areas of least and most building-imposed wind and climatic wind interaction.

4.0   CONCLUSIONS AND RECOMMENDATIONS

     An enhanced heliport wind assessment tool would provide an effective
means for evaluating and potentially minimizing the influence of wind on
heliport operations. As illustrated in Section 3.0, this tool can be
further developed into a simplified methodology that could be used by
non-technical personnel to evaluate and select the most favorable
heliport site based on prevailing conditions. In addition, the impact of
new construction on existing heliports could be determined. The need for
such a tool is increasing as the development of city center heliports in
the near proximity to buildings is expanding.

     It is therefore recommended that further test and evaluation be
pursued to validate and enhance the heliport wind assessment
methodology. Such an effort would entail the following tasks:

     1. Collect Helicopter Performance Limitation Data
         Collect for each helicopter type, gust speed
         limitation data and divide the data into two or
         three major groups. Computer simulation of
         helicopter handling qualities could provide much of
         the data needed. Also survey helicopter pilots to
         determine preferred (self-imposed) operating limits
         in winds (e.g. passenger comfort, etc.) and compare
         to actual recommended limitations. Further
         rearranging of the helicopter types within the gust
         speed groups may be necessary. This effort will
         establish the wind gust and velocity conditions on
         which to perform wind tunnel testing that will tie
         helicopter performance to the building wind
         environment.

     2. Wind Tunnel Testing
         Wind tunnel testing should be performed for both
         single and multiple building configurations and for
         wind conditions defined in Task 1. Data gathered
         during this testing, together with existing data,
         would be used to evaluate the influence areas both
         of the ground surface and for various heights along
         the building. Evaluation would determine which
         building types and multiple building configurations
         can be generalized and finally reduced to general
         rules to define wind influence areas.

     3. Develop General Rules
         Develop general rules for calculating the wind
         influence area for any particular building
         configuration, at various heights (floors) of the
         building, and for types of helicopters anticipated
         to operate in the building vicinity.

REFERENCES

1. Newberry, C.W., and Eaton, K.J., "Wind Loading Handbook", Department of Environment, Building Research Establishment, London, Her Majesty's Stationary Office, 1974.

2. Gandemer, J., "Wind Environment Around Buildings: Aerodynamic Concepts", Centre Scientifique et Technique du Batiment Nantes France, ≃ 1976.

3. Beranek, W.J., "General Rules for the Determination of Wind Environment", Institute TNO for Building Materials and Building Structures (IBBC), reprints from the Fifth International Conference on Wind Engineering, Colorado State University, Volume I, Sessions I-V, 8-14 July, 1979.

4. Beranek, W.J. and Koten, H.V., "Beperken van windhinder om gebouwen", Part 2, Stichting Bouwresearch, ≃ 1980. (In Dutch)

5. Gandemer, J., "Wind Environment Around Buildings, Aerodynamic Concepts", Proceedings of the fourth International Conference Wind Effects on Buildings and Structures, Heathrow, 1975.

6. Gandemer, J. and Guyot, A., "Integration du phenomene vent dans la conception du milieu bati", 1976.

7. Davenport, A.G., et.al., "A Wind Tunnel Evaluation of the U.S. Steel Building Heliport", The University of Western Ontario, BLWT-1-68, February 1968.

8. Surry, D., and Stone, G.K., "A Study of the Effects of the Proposed Rockefeller University Facility Housing Project on Nearby Helicopter Operations and the Adjacent Building", The University of Western Ontario, BLWT-SS12-1983, May 1983.

9. Lemberg, R., "On the Wakes Behind Bluff Bodies In a Turbulent Boundary Layer", The University of Western Ontario, BLWT-3-73, April 3, 1973.

10. Logan, E., and Chang J., "Wake Characteristics of Buildings in Disturbed Boundary Layers", NASA Marshall, NASA CR 3284, May 1980.

11. Steely, S.L., and Frost, W., "Statistical Analysis of Atmospheric Turbulence About a Simulated Block Building", The University of Tennessee Space Institute, NASA CR 3366, January 1981.

12. Just, W., "Investigation of Air Turbulence on Heliports", Journal of the American Helicopter Society, Vol. 2, No. 3, July, 1975.

REFERENCES (Continued)

13. Teunissen, H.W., "Wind Tunnel Investigation of the Air Flow Over a
    Model Apartment Building", Atmospheric Environment Service, Internal
    Report No. MSRB-80-2, April 1980.

14. Corke, T.C., et.al., "Flow Near a Building Model In a Family of
    Surface Layers", Journal of Industrial Aerodynamics, 5 (1979)
    139-158, April 1979.

15. Isyumor, N., and Davenport, A.G., "Evaluation of the Effects of Tall
    Buildings on Pedestrian Level Wind Environment", ASCE Annual
    Convention, October 16-20, 1978.

16. Davies, M.E., and Miller, B.L., "Wind Effects on Offshore Platforms –
    A Summary of Wind Tunnel Studies", National Maritime Institute, NMI
    R140, OT-R-8215, June 1982.

END

FILMED

6-85

DTIC